

# Organic waste streams in energy and biofuel production

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University of Applied Sciences

# ORGANIC WASTE STREAMS IN ENERGY AND BIOFUEL PRODUCTION

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## TERMINOLOGY

**AD**, Anaerobic Digestion

**BTL**, Biomass to Liquid

**CHP**, Combined Heat and Power

**DDGS**, Dried Distillers Gains with Solubles

**DME**, Dimethyl Ether

**GHG**, Greenhouse Gas

**MSW**, Municipal Solid Waste

**OSF**, Official Statistics of Finland

**PSA**, Pressure Swing Adsorption

**TOC**, Total Organic Carbon

**TSA**, Temperature Swing Adsorption

**CH<sub>4</sub>**, Methane

**CO**, Carbon Oxide

**CO<sub>2</sub>**, Carbon Dioxide

**H<sub>2</sub>**, Hydrogen

**H<sub>2</sub>O**, Water

**H<sub>2</sub>S**, Hydrogen Sulfide

**HF**, Hydrogen Fluoride

**N<sub>2</sub>**, Nitrogen

**NO<sub>x</sub>**, Nitrogen Oxides

**O<sub>2</sub>**, Oxygen

**SO<sub>2</sub>**, Sulfur Dioxide

# FOREWORDS

The future is in our hands, and it is certain that it will not be easy. Cooperation in research and development, great ideas and objectives, will take us further and further. We should start to create international activities, relationships and action at a whole new level. We all must have the courage to step out of the comfort zone.

I appreciate the work at Kymenlaakso University of Applied Sciences, which together with other actors, has boldly done research in the bioenergy-field. Business cooperation with international partners is not always easy. Results will be slow, and sometimes you get nothing. For us, it would be a relief if we could say that the future is secure, cleantech business is running and energy is sufficiently available. Genuine accountability is unfortunately rare. That is why companies need to support research and development.

We are faced with a huge amount of potential. Cleantech business can secure the future of Finland, if citizens, businesses and politicians decide to work together on behalf of more sustainable business. For example, the waste we all produce contains a lot of exclusive material. Now it goes to incineration or, in the worst case, to landfill, depending on how sophisticated the waste consumer at source is. When another entrepreneur is having problems with the cost of expensive material, usable raw material may be buried in the ground.

We need educational institutes, as active operators, to bring together “providers” and “consumers”. We need more research to solve the problems with which companies on a daily basis are grappling. One example of this is landfill gas purification. We should extract hydrogen sulfide from landfill gas more effectively. When a solution is found, we are able to exploit the gas as energy and society is then another step closer to a perfect tomorrow.

*Annika Aalto-Partanen*

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# I INTRODUCTION

This research is being done for project BLESK, which is funded by the South-East Finland – Russia ENPI CBC –program. This study is about bioenergy and its area of focus is utilization of organic waste streams in energy recovery and biofuel production. The aim of this report is to present modern technologies in the field of municipal waste energy recovery. This study can be applied for educational purposes and to provide general information on modern solutions in the field of bioenergy. The main topics of this research are waste combustion, liquid fuels and biogas.

This study takes a stand on current law and regulations and possible future changes in legislation in municipal waste utilization. Waste-to-energy appliances are presented as one option but current legislation prefers recycling and other ways of reusing the waste streams. This includes biofuel productions like biodiesel, renewable diesel and bioethanol in addition to biogas production from landfills or biodegradable waste streams.

The European Commission has implemented a directive which obliges Member States to reduce the amount of waste brought to the landfills. Specifically this means that the amount of biodegradable waste that is brought to landfills must be 35% of the 1995 level by 2016. The aim of this directive is to reduce GHG emissions. The directive is called the Landfill Directive (1999/31/EC). (European Commission. Biodegradable Waste. 2014)

The directive does not regulate how this reduction is done. In practice, most countries rely on easy methods like combustion of the waste instead of utilizing it in biofuel and biogas production. Biofuels and biogas would have a much higher retail price than waste incineration and as such should be the preferred method of waste reuse. (European Commission. Biodegradable Waste. 2014)

## 2 LAWS AND REGULATIONS

The European Union has set laws and regulations with the aim of reducing greenhouse gases (GHG) to prevent global warming and promote renewable energy solutions. One of the goals is to reduce the amount of municipal waste brought to landfills. This is implemented through better waste stream management. Waste incineration and landfill disposal are not considered a good option. Effective waste treatment and utilization of biodegradable waste streams in biofuel production contributes to the production of bioenergy and GHG reduction in addition to minimizing the amount of disposed waste.

The European Union aims to have 20% of energy production covered by renewable sources by 2020. Biofuels and biogas are one of the ways to contribute to this goal. Biofuels could be used as a fuel blend in traffic fuel while biogas could be a potential substitute for natural gas and can be transferred into the existing natural gas network. Biofuels and biogas can be utilized in CHP processes and upgraded biogas is a viable option as traffic fuel as well (European Commission, EU researchers investigate biogas potential).

The following waste sources are considered biowaste streams by the European Commission:

- biodegradable garden and park waste
- food and kitchen waste
- household waste
- restaurant waste
- catering waste
- retail premises waste
- waste which comparable to waste from food processing plants

The following waste streams are not included in the biowaste category by definition of European Commission:

- forestry and agricultural residues
- manure
- sewage sludge
- nature textiles
- paper
- processed wood (European Commission, Biodegradable Waste)



**Laws that apply to landfills in Finland** set strict demands on how to prevent hazards and harmful events. This also creates boundaries for landfill gas utilization. The following list presents things that must be taken into account at landfills in Finland.

- Stability of the waste pile
- Littering of the environment
- Littering of the public roads
- Noise and harm to traffic
- Harm caused by pests
- Smell, dust and aerosol harm
- Risk of fire
- Frost-heave

Things mentioned in the list must also be taken into account as any similar events that could occur. This demand is set by the government decree on landfills in regulation 331/2013, Section 11 (Finlex 331/2013).

Due to EU policy, the Finnish government set a regulation at 1 June 2013 that limits the amount of organic waste which can be disposed of at landfill. The law states that, from 1 January 2016, waste that is disposed of at landfill or used in soil filling may not contain more than 10% organic material. The regulation also sets the same limits for decommissioning and construction waste but this will not enter into force until 2020. The aim is to stop disposal of organic material at landfills and utilize it for material purposes and in energy production by 2016 (Ministry of the Environment. Valtioneuvoston asetus rajoittaa orgaanisen jätteen sijoittamista kaatopaikalle).

**The Government Decree on waste incineration** states that emissions to air and water must be measured. Section 18 of this decree states that measurements must be done to those gas components, conditions and variables which are significant in the incineration process. Section 18 states that emissions which are released into the atmosphere from incineration plants must be measured continuously. This regulation applies to the facilities mentioned in Section 1 such as waste incineration power plants. The gas components which must be measured are NO<sub>x</sub>, CO, total particulate matter, TOC content, HCl, HF and SO<sub>2</sub> (Finlex 151/2013).

Section 4 of 151/2013 also sets detailed general demands for the organization of operation. It also refers to the Environmental Protection Act 86/2000 by announcing that the procedures presented in it must be taken into account as well as the procedures presented in 151/2013. Section 9 of 151/2013 also sets demands for burning temperature and combustion hold time, and Section 8 states that energy released from combustion must be recovered. (Finlex 151/2013)

**According to Section 5 of the Finnish Subsidy Act, biogas is gas produced via anaerobic fermentation.** Biogas-producing facilities can be accepted in the feed-in tariff system. Requirements that need to be fulfilled are defined in Sections 7 and 10. One of the demands which must be fulfilled is the nominal electricity output which must be over 100 kVA (Finlex 1396/2010).

**The Fertilizer Product Act 539/2006** has an effect on the by-products of anaerobic reactors. According to Section 2 of the act, digested sludge can be used as fertilizer unless the by-products are unsuitable for fertilizer use. The purpose of the act is to guarantee the quality and safety of fertilizers. It is also mentioned in Section 5 that fertilizers must be even in quality, suitable for use as well as safe to use (Finlex 539/2006).

**The Subsidy Act 1396/2010** clearly states in Section 1 that its purpose is to promote production of electricity in the area of renewable energy. According to Section, biogas production is eligible for production subsidy in the form of a feed-in tariff. The same section states that the law can also be applied to, for example, wood fuel-based electricity production (Finlex 1396/2010).

# 3 WASTE STREAMS

Municipal solid waste is a potential source of renewable energy as well as a source of re-usable materials. Due to this fact, both financial and environmental benefits should be considered in the field of MSW utilization. There are multiple routes for the energy recovery of MSW such as direct incineration, production of liquid fuels and anaerobic digestion for biogas. Direct incineration is often the easiest way but is not the preferred method according to EU waste policy. Liquid fuel and biogas production upgrades the retail value of waste more and they should be produced instead of direct incineration.

Sustainability is driven by the EU waste policy as seen in Figure 3.1. The EU waste hierarchy prefers prevention, re-use and recycling over energy recovery and disposal. However, recycling can be carried out on the side of energy production, for example in the form of the gasification of aluminous waste, thus allowing recovery of aluminium.

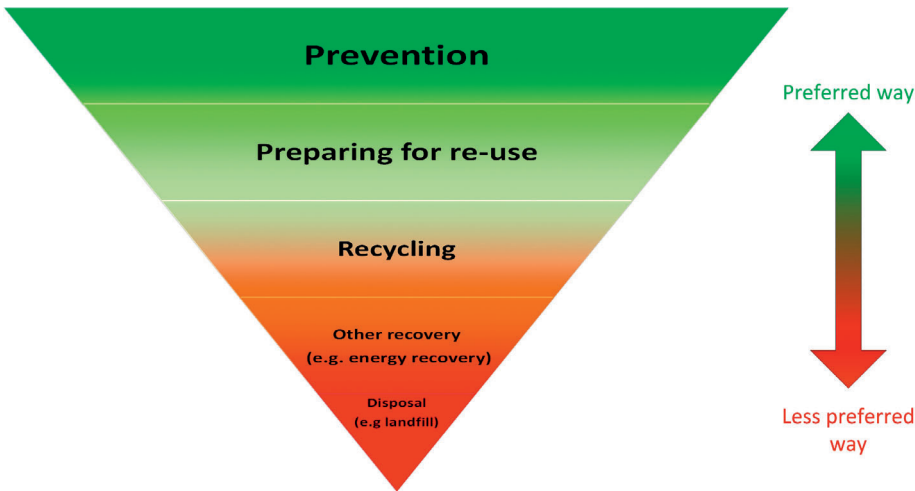


Figure 3.1. The waste hierarchy defined by EU policy. Adapted from: European Environment Agency. Managing municipal solid waste. EEA Report No 2/2013.

Municipal waste can be divided into subcategories such as unsorted, assorted and recycled waste. Unsorted waste includes a mix of waste produced by households, restaurants, etc., while assorted and recycled waste are considered pre-sorted waste. Recycled waste is categorized as separately collected waste, whereas assorted waste is considered to be sorted mixed garbage. Sorting divides the materials into different fractions, thus reducing the amount of organic waste dumped in landfill as required by the Landfill Directive (1999/31/EC) Article 1 (EUR-Lex. Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste).

The following Figure 3.2 illustrates how waste management is implemented in Finland. There are different routes which mainly lead to utilization facilities such as assorting and to energy recovery facilities such as waste incineration power plants. This leads to reduced landfilling. However, as can be seen from the figure, there are also various routes to the disposal site such as landfill.

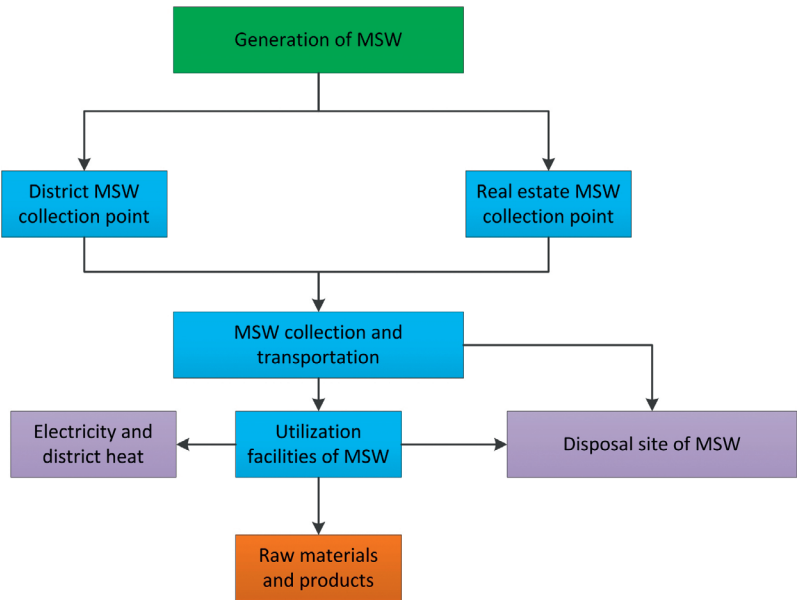


Figure 3.2. Waste management (Finnish Solid Waste Association. Suomen yhdyskuntajätehuolto).

The following table 3.1 shows municipal waste produced in Finland in 2012. The treatment part of the table illustrates that the utilization of the organic waste is within EU requirements.

Table 3.1. Municipal waste in Finland in 2012 (Official Statistics of Finland)

Municipal waste in Finland year 2012 (Amount in tonnes)	Amount	Treatment		
		Recycling	Energy recovery	Landfilled
Mixed waste total	1 394 746	6 171	519 761	868 814
Separately collected waste total, of which	1 203 148	894 014	297 473	11 661
Paper and board waste	364 902	327 904	36 986	12
Organic waste	363 259	328 445	31 270	3 544
Glass waste	30 476	29 947	..	529
Metal waste	123 915	123 913	1	1
Wood waste	78 563	3 793	74 769	1
Plastic waste	36 127	4 451	31 676	0
Electrical and electronic scrap	67 871	67 829	42	..
Other	140 201	12 411	107 591	20 199
All total	2 738 095	912 596	924 825	900 674

The following figure illustrates the total waste stream percentages in 2012 in Finland. The figure clearly shows that in Finland recycling, energy recovery and landfill streams have similar quantities of roughly 33% of all waste. Data from Table 3.1 and figures 3.3 and 3.4 is from OSF data released on 26.11.2013.

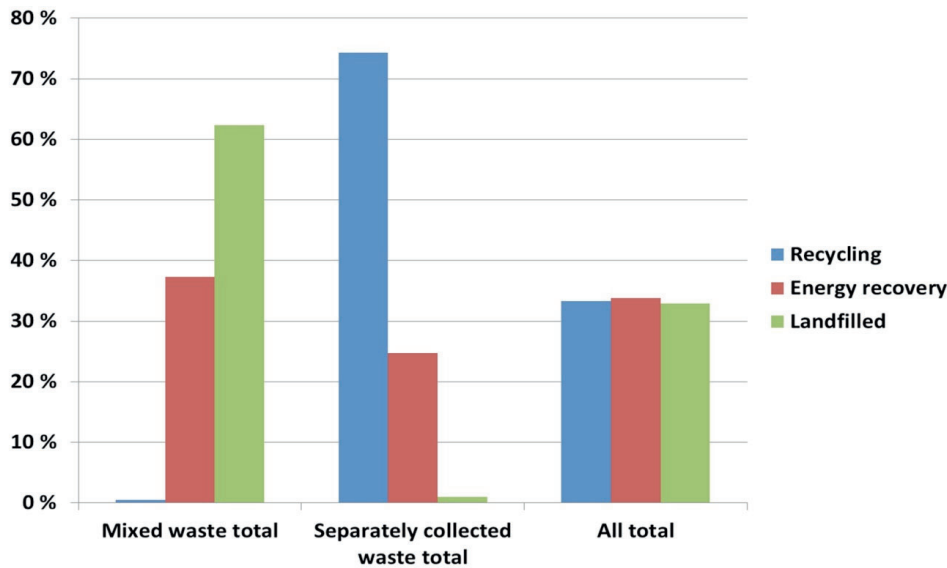


Figure 3.3. Total municipal waste streams in Finland 2012

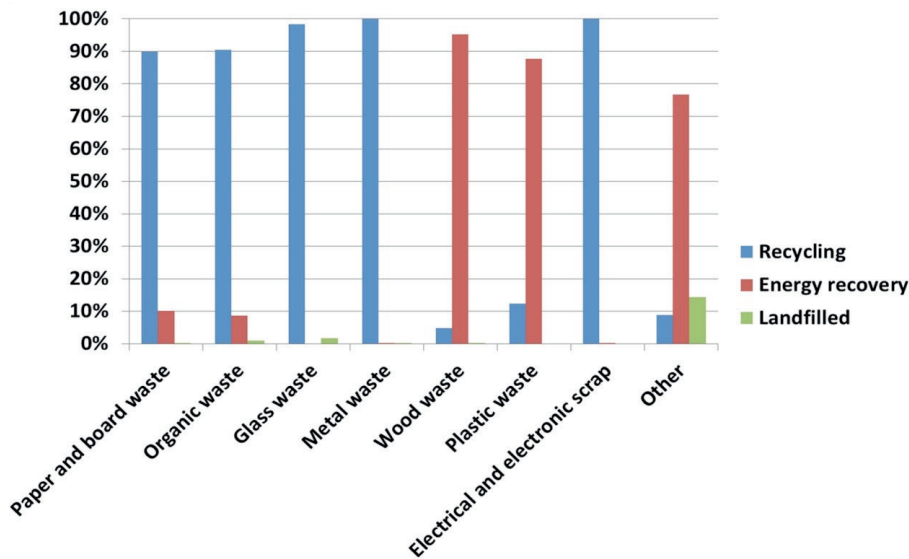


Figure 3.4. Separately collected municipal waste streams in Finland 2012

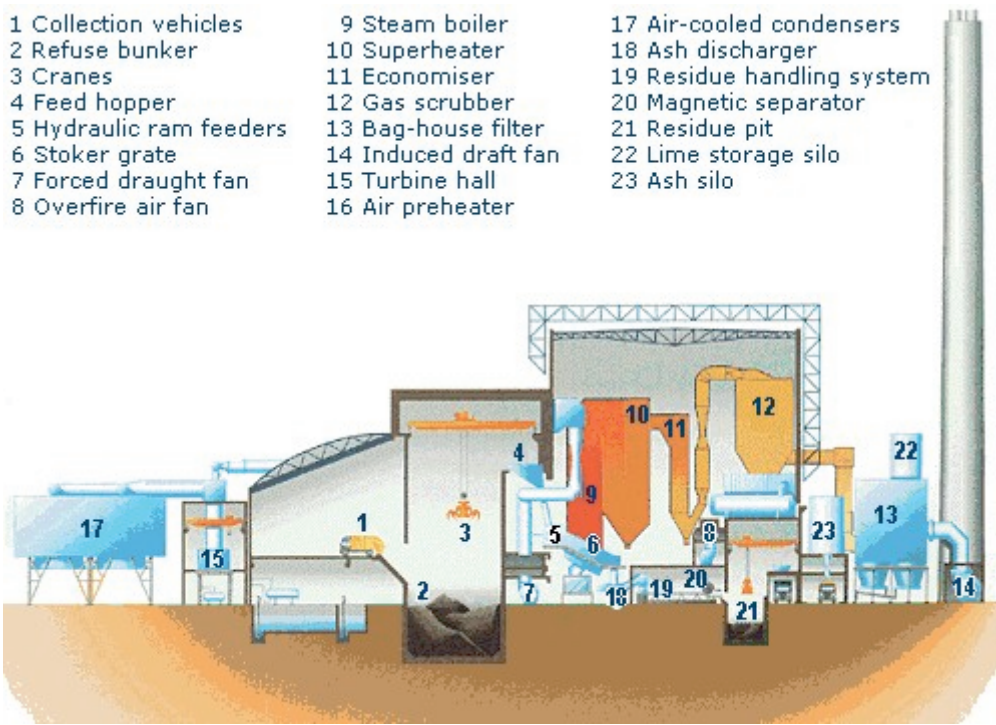
The following figure 3.4 illustrates how the waste streams of separately collected waste are distributed to different fractions. From the figure, we can see that materials such as wood are most often utilized in energy recovery whereas materials like paper and metals are recycled. The method of utilization is often determined by the easiest solution available, which means that the wood is mostly used in incineration processes whereas metals can be easily re-used in new products.

According to the OSF released on 26.11.2013, the incineration of municipal waste has been increasing since 2006. This can be seen in statistics as an increase in energy recovery and decrease in material streams to landfill. Regardless of increased municipal waste incineration, the recycling of waste has not decreased (Official Statistics of Finland (OSF): Waste statistics [e-publication]).

# 4 MUNICIPAL WASTE INCINERATION

Municipal waste incineration can be utilized in the production of electricity and heat. In addition, under proper conditions it reduces the volume of waste going to landfill, reduces the net amount of toxins and, unlike municipal waste itself, the produced ash can be used as an additive for concrete. However, it should be noted that waste incineration also has higher investments costs than landfill.

Waste burning for energy applications requires good flexibility in general since municipal waste contains a wide range of fuel properties such as moisture and calorific values. This easily leads to varying demand for fuel fed to boilers, which leads to difficulty in energy production and emission control.



Basically, waste incineration utilizes three different kinds of technologies in addition to the steam boiler process for increased efficiency:

- Grate incineration
- Fluidized bed incineration
- Rotary kiln incineration

Grate incineration utilizes a fixed or moving metal grate as an incineration base. Figure 4.1 illustrates grate firing in waste incineration. In municipal waste applications, variable feedstock (moisture, heating value) usually requires a large mixing silo to ensure homogenous fuel feed. Municipal waste is burned at a high temperature with sufficient residence time to ensure that most of the toxic substances disintegrate. Some countries also require gas burners to ensure that the sufficient holding time for flue gas temperature is achieved.

Rotary kiln furnaces are long sloping cylinders where the fuel slowly burns and moves downstream. Supplementary fuel is normally used to ensure thorough incineration of waste-derived fuel. Rotary kilns can be fed with almost any kind of waste without harmful consequences, and in fact some designs prefer a thin layer of glasslike slag as it protects the drum medium from harmful intermediate products produced in waste incineration (Metso, Rotary Incineration).

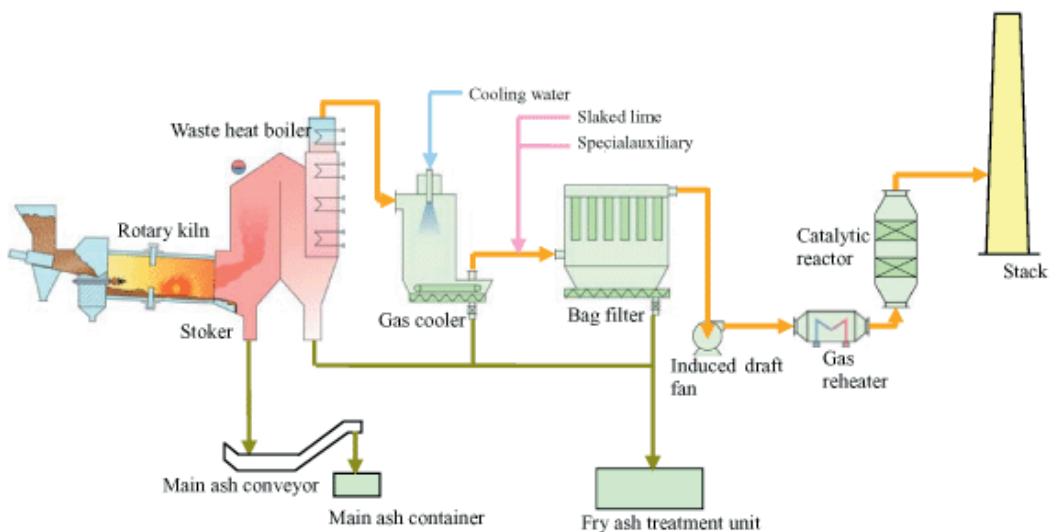


Figure 4.3 Rotary kiln incinerator (Global Environment Centre Foundation. Hitz Rotary Kiln Incineration Plant)

Bubbling fluidized-bed (BFB) incineration utilizes a bed of sand which is fluidized by blowing the combustion air through it, and waste is fed on the top of the bed where it incinerates over time. Figure 4.2 illustrates the basic fluidized-bed process. It should be noted that fluidized-bed appliances require some sorting because the possible metals cause sintering of a bed material, which in turn obstructs the ground ash removal channels. In fluidized bed appliances, limestone can easily be used as a sand addition to neutralize possible acid formation. High mass and movement of the fluidized-bed also ensures that heat and fuel are evenly distributed to the bed and combustion is as complete as possible. It is also possible to use a circulating fluidized-bed (CFB)



in waste incineration, but these require more processing of waste to ensure stable incineration. CFBs usually prefer RDF (refuse derived fuel) as fuel because it is more homogenous.

In all municipal waste incineration appliances, the resulting flue gas must be cleaned in order to ensure that the emission limits are met. Waste incineration for instance produces some air pollutants not met in conventional incineration appliances like biomass, coal and natural gas incineration. In order to meet strict emission limits, modern emission control measures should be taken and, with correct emission control measurements, waste incineration can actually compete with conventional power plants in emissions quantities. These include:

- Proper control of incineration to ensure thorough burning of waste
- Ammonia injection for  $\text{NO}_x$  (nitrogen oxide) reduction
- Flue gas scrubber for  $\text{SO}_x$  and acid gas reduction
- Injection of activated carbon for mercury and dioxin reduction

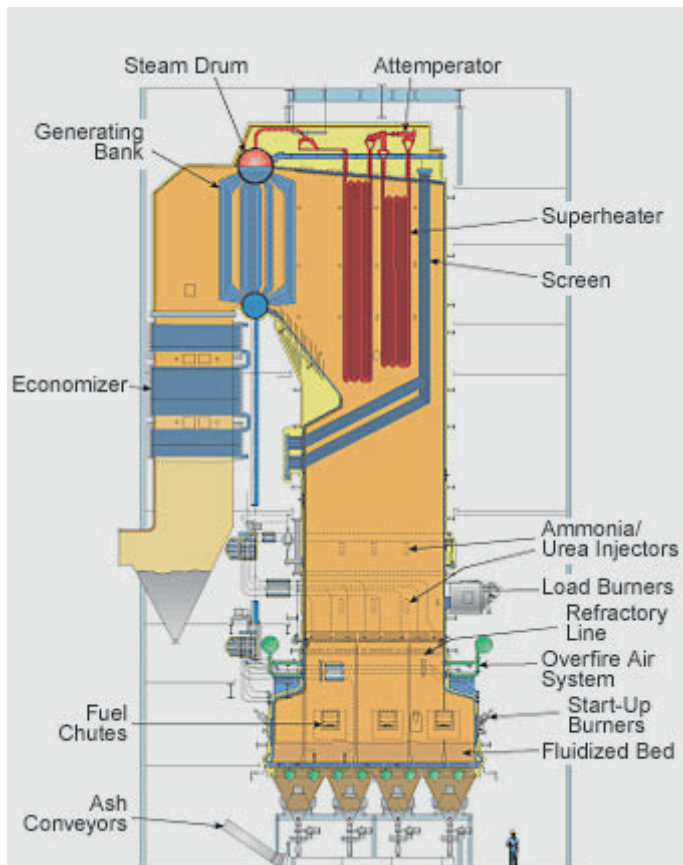


Figure 4.2 Bubbling fluidized-bed incinerator. (ASME, Fluidized-DBed Combustors for Biomass Boilers)

## 5 LIQUID FUELS

Fatty acid and biodegradable waste can be converted into several kinds of different liquid fuels using different kinds of technologies. Nowadays the most common types of biofuel are biodiesel, renewable diesel and bioethanol, both of which can be produced completely from industry and municipal waste streams with current technologies. However, most of the liquid biofuels are still produced from feedstock competing with food production.

Basically, all biofuels competing with food production are classified as 1<sup>st</sup> generation biofuel, and biofuels produced from the waste streams or feedstock not competing with food production are classified as 2<sup>nd</sup> generation biofuels. The following feedstock, waste streams and biodegradable materials can be converted into biofuels:

- Cereal crops and sugar crops for 1<sup>st</sup> generation bioethanol
- Oil crops and vegetable oils for 1<sup>st</sup> generation biodiesel
- Energy crops, algae, agricultural residues, waste streams and forestry resources for 2<sup>nd</sup> generation bioethanol
- Fatty acid waste streams and tall oil for 2<sup>nd</sup> generation renewable diesel (European Bio-fuels Technology Platform. Biofuel production)

Figure 5.1 represents the basic production chain of biodiesel and renewable diesel. Oil-producing plants (rapeseed, palm, soya, sunflower, etc.) used as a feedstock are marked with a green rectangle. The main processes (pressing and extraction, esterification, hydrogenation and separation) are marked with a blue parallelogram. By-products (animal feed and glycerol) of biodiesel and renewable diesel production are marked with brown rectangles. The biodiesel production chain requires alcohol (methanol or ethanol) as chemical input but in turn produces glycerol as a by-product. Renewable diesel on the other hand requires hydrogen as chemical input and produces no by-products.

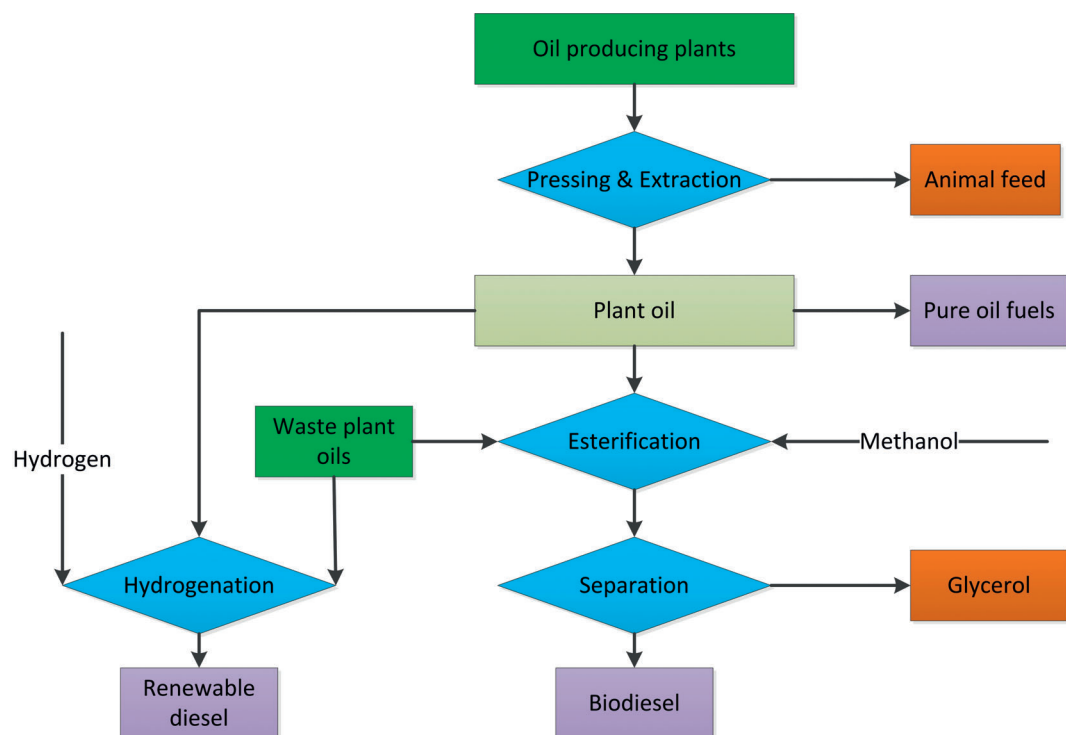


Figure 5.1 Renewable diesel and biodiesel from vegetable oils. Adapted from (European Biofuels Technology Platform. The production of biofuels from vegetable oils)

## 5.1 1<sup>ST</sup> GENERATION BIODIESEL

All of the 1<sup>st</sup> generation biodiesels are, by EU definition, esters and have somewhat different properties to petroleum diesel. For example, they are somewhat more volatile than petroleum products, thus limiting their shelf life. However, most of the new diesel engines can operate with almost any blend of biodiesel and petroleum diesel without any problems.

The process used for fatty acid esterification is called transesterification. The basis of the process is the replacement of the triglycerides glycerin group with another alcohol, resulting in three separate esters. The replacing alcohol is most commonly methanol or ethanol. However, there have been some studies with more complex alcohol groups for better biodiesel quality (European Biofuels Technology Platform. Biofuel production).

The advantages of FAMEs (Fatty acid methyl esters) include higher cetane number and better lubricity. Higher cetane number results in smoother engine operation, especially with older diesel engines. Better lubricity also makes biodiesel a viable fuel additive in increasing the lubricity of low-sulfur petroleum diesel. Most of these properties can be attained with minimum biodiesel blending.

FAME biodiesel usually has slightly lower heat in combustion, variable cold properties, slightly higher viscosity and some problems with oxidative stability when compared to petroleum diesel.

The lower heat of combustion results in lower power output with the same amount of fuel, but this can be compensated by feeding more fuel. Cold properties of biodiesel vary from quite low to quite good depending on the fatty acid composition of feedstock. There has been some research on the effect of fatty acid composition and refining it. The viscosity of biodiesel also varies according to the fatty acid composition and is usually slightly higher than with petroleum diesel, which might cause problems with some engines. Auto-oxidation is one of the biggest concerns with biodiesel, because it severely lowers biodiesel's properties. However, with proper additives, biodiesel can actually last quite long (National Center for Agricultural Utilization Research. National Center for Agricultural Utilization Research).

## 5.2 2<sup>ND</sup> GENERATION RENEWABLE DIESEL

The successor to 1<sup>st</sup> generation feedstock-produced biodiesel is 2<sup>nd</sup> generation non-feedstock-produced renewable diesel. The advanced 2<sup>nd</sup> generation renewable diesel is CO<sub>2</sub> free, excluding production and logistics, even though it is composed of alkanes just like petroleum diesel. 2<sup>nd</sup> generation renewable diesel is an advanced biofuel so it is counted as double when calculating EU renewable energy targets (European Biofuels Technology Platform. Biofuel and sustainability issues).

Currently there are a couple of processes for 2<sup>nd</sup> generation biodiesel, but most of them are based on hydrogenation of fatty acids (vegetable oils and fats) for hydrocarbons or gasification of biomass for syngas and the Fischer-Tropsch process for refining syngas.

- NExBTL by Neste Jacobs utilizes hydrogenation of vegetable oil and waste fats to produce hydrocarbons. Hydrocarbons are isomerized into heavier hydrocarbons to produce alkane diesel (Neste Oil. Uusiutuva NExBTL).
- BioVerno by UPM Bioenergy utilizes the hydrogenation of tall oil to produce alkane diesel with similar constitution to petroleum diesel (UPM Bioenergy. UPM ja tulvavaikeiden polttoaineet. 2012)
- Future processes include thermochemical routes like gasification of biomass combined with Fischer-Tropsch synthesis as illustrated on figure 5.2 (Neste Oil. NExBTL Renewable diesel)

2<sup>nd</sup> generation renewable diesel has a similar molecular structure to petroleum diesel. As such it can be used as any blend in all diesel engines without any problems. However, there are some discrepancies between the 2<sup>nd</sup> generation renewable diesel and petroleum diesel, most notably in cloud point and density. 2<sup>nd</sup> generation renewable diesel also has a requirement for high level of sustainability, which can only be met by using non-feedstock feedstock (Neste Oil. NExBTL Renewable diesel).

## 5.3 BIOETHANOL

Bioethanol can be used as a substitute or a blend component for petroleum gasoline. Currently most cars can use up to 10% blend of ethanol and gasoline while flex-fuel cars can use almost any blend of ethanol and gasoline ranging from 20-100%, but they do not take full benefit from the increased octane rating of ethanol. To take advantage of the increased octane rating of ethanol,

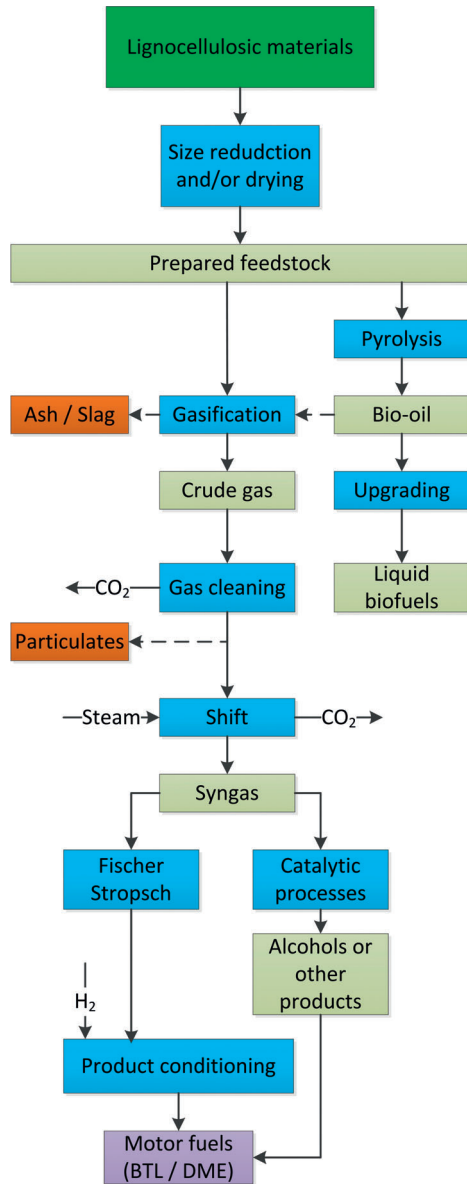


Figure 5.2 Thermochemical biofuel production (European Biofuels Technology Platform. Thermochemical routes to liquid biofuels. 2007)

cylinder, turbocharger and fuel supply modifications are needed (Technology Review. A more efficient ethanol engine. 2009).

Bioethanol can also be seen as a potential substitute for groundwater-contaminating MTBE (methyl tert-buthyl ether), ETBE (ethyl tert-buthyl ether) and harmful TEL (tetraethyl lead) as a fuel additive for increasing the octane rating of petroleum gasoline. However, ethanol has some problems with oxidative stability, which could be improved with proper additives. Ethanol also has inferior cold-start properties to gasoline, which could limit the maximum blend in colder environments.

Bioethanol can basically be produced from three different kinds of biomass with fermenting. The most common process in Europe is direct fermenting of diffusion-pressed sugar crops (sugar beet), which has the highest yield and requires the least processing from crop to ethanol. In the US, starch crops like corn are preferred because they are inexpensive. Other starch crops, starch crop waste and biodegradable waste can also be used in ethanol production by utilizing the enzymatic degradation of starch to sugars. Future processes include converting the cellulosic biomass and bio waste into fermentable sugars with enzymes. With proper planning, cellulosic biomass does not compete with food production, so it will most likely dominate the ethanol production process in the future.

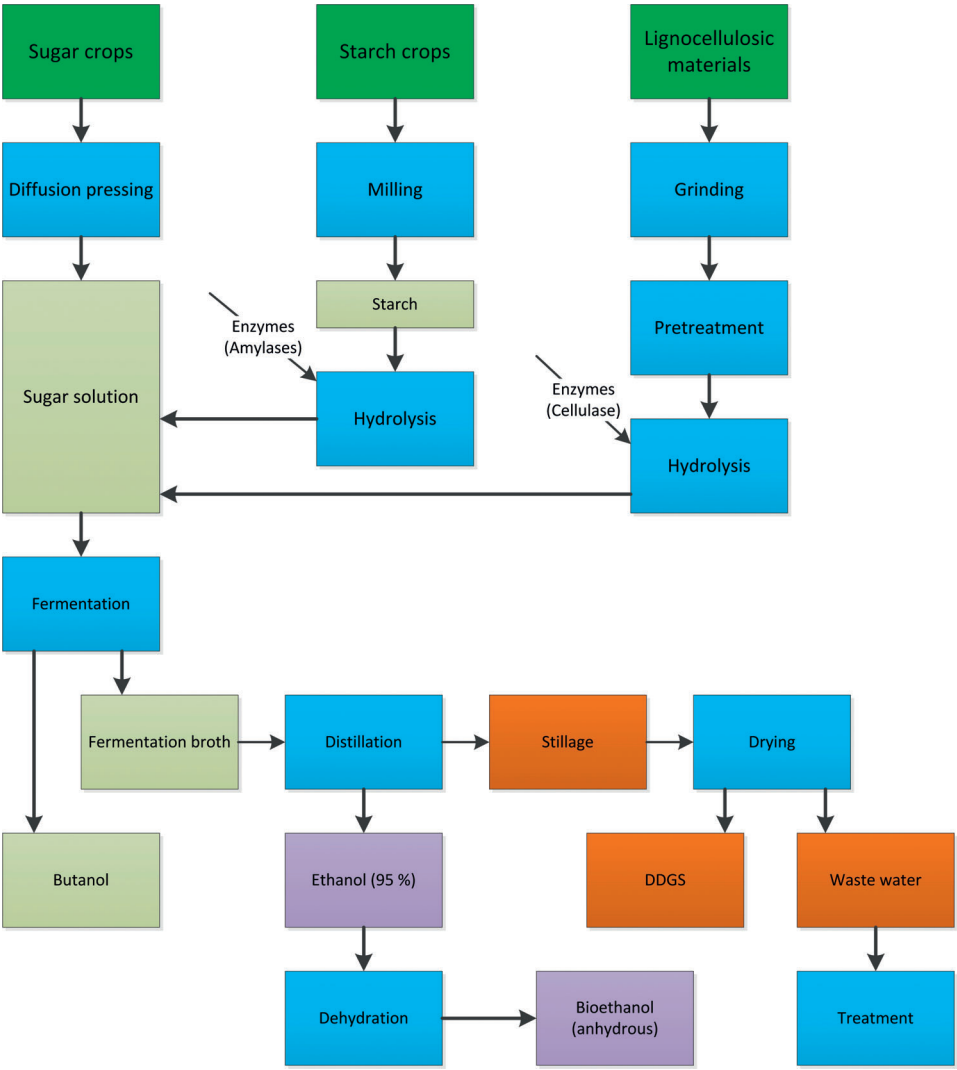


Figure 5.3 Ethanol from sugar crops, starch crops and lignocellulosic materials. Adapted from (European Biofuels Technology Platform. Biochemical routes to liquid biofuels. 2007)

As presented in Figure 4.3, ethanol can be produced from sugar crops, starch crops or lignocellulosic material. The cheapest process (excluding feedstock costs) is the diffusion-pressing of sugar crops for sugar solution. Starch crops require milling and enzymatic hydrolysis to produce sugar solution, while lignocellulosic materials require grinding and thermochemical treatment to separate lignin and cellulose in addition to enzymatic hydrolysis.

Yeast is added to sugar solution to produce ethanol and  $\text{CO}_2$  from simple sugars. Ethanol solution is distilled to the 95% ethanol concentration and possibly dehydrated to anhydrous (100%) ethanol for petroleum fuel blending. The stillage from ethanol production can be directly used as animal fodder or can be dried to DDGS (Dried Distillers Grains with Solubles) for increased shelf life (European Biofuels Technology Platform. Biochemical routes to liquid biofuels. 2007)

## 6 BIOGAS

Biogas has been produced for centuries around the world. Biogas forms naturally under suitable conditions like swamps and landfills. It can also be produced by digesting organic material in a controlled environment in order to collect the biogas. At landfills, biogas can be collected by implementing a pipe network inside the landfill. Biogas is considered to be a renewable and environmentally-friendly fuel source and will not increase the level of CO<sub>2</sub> (carbon dioxide) in the atmosphere.

Upgraded biogas, also known as biomethane, can be as good a fuel source as natural gas. It can be used as a replacement fuel for natural gas in applications such as gas engines and burners. The natural gas heating value is approximately 36 MJ / m<sup>3</sup>(n) and for biogas it usually ranges from 10 MJ / m<sup>3</sup>(n) for un-upgraded to approximately 35 MJ / m<sup>3</sup>(n) for upgraded biogas.

Before raw biogas can be fed into the natural gas grid or gas turbine, it usually needs some of the following operations:

- pre-drying for coarse water separation
- pressurizing (3.5 – 400 bar depending on usage)
- drying to remove moisture
- filtering to remove solid particles

Biogas is generated by anaerobic digestion of organic material via bacterial disintegration. The first documentation of a controlled anaerobic digestion was done in the United Kingdom in 1895. In India and China, anaerobic digesters have been utilized for biogas production on a small scale and the biogas produced is mainly used for lighting and cooking. In European and North American countries, biogas production on an agricultural scale is done utilizing the latest technologies for optimized biogas production (Biogas Handbook, 2008. Page 7).

There are basically three different AD (anaerobic digestion) processes (psychrophilic, mesophilic and thermophilic), which deviate in process temperature and bacteria used. The thermophilic and mesophilic processes are favoured in modern digesters while the psychrophilic process is more likely to occur naturally, for example in landfills. The following table 6.1 illustrates the process temperature ranges, retention times and yields.



	Process temperature	Retention time	Yield
	°C	days	-
Psychrophilic	< 25	70 to 80	Low
Mesophilic	25 to 45	30 to 40	Medium
Thermophilic	45 to 70	15 to 20	High

Table 6.1 Anaerobic digestion processes

Stages of anaerobic digestion include:

- **Disintegration** is the first step in anaerobic digestion. Disintegration decays material into smaller particulates such as carbohydrates, lipids and proteins.
- **Hydrolysis** is a phase where proteins, lipids and carbohydrates are depolymerized. Hydrolysis forms lipids, simple sugars and amino acids. These enzymes can be degraded further in following steps of the process.
- **Acidogenesis** is a phase that can also be referred to as fermentation. In this phase, simple monomers form volatile fatty acids, organic compounds and alcohols.
- **Acetogenesis** phase forms acetic acids from organic molecules and volatile fatty acids. This phase also forms carbon dioxide and hydrogen. The reactions are caused by acetogenic bacteria.
- **Methanogenesis** is the last phase of anaerobic digestion. In this phase, methane is produced from acetic acid by acetolastic methanogens or from hydrogen and carbon dioxide by hydrogenothrophic methanogens.

(Woodhead Publishing Limited, 2011. page 267-268)

The following figure 6.1 presents the anaerobic digestion process in a simple form. Actions from the previous list can be seen from the figure in the order in which they occur.

Biogas consist mainly of methane and carbon dioxide. It is formed by degradation of organic matter under anaerobic conditions. The quality of biogas depends greatly on the feedstock and production technology. Typically biogas CH<sub>4</sub> (methane) content varies from 40% to 75% and the CO<sub>2</sub> (carbon dioxide) content varies from 30% to 45%. Biogas also includes moisture and some trace elements such as hydrogen sulfide and siloxanes. Upgrading is used to remove biogas from un-wanted gases (carbon dioxide, hydrogen sulphide and siloxanes). After upgrading, the methane content (95 – 98%) and other properties of biogas are similar to natural gas.

Biogas production increases the energy self-sufficiency by utilizing biodegradable waste streams in energy production. As a side product the digested sludge can be used as fertilizer to return valuable minerals and micronutrients to food production instead of being wasted (Kymen Bioenergia). Typical components of biogas and their ranges are presented in Table 6.2. This table is based on multiple sources. Due to the variable feedstock used in biogas production, the gas element concentrations in biogas may vary. Silicon compounds and siloxanes usually occur only in landfills.

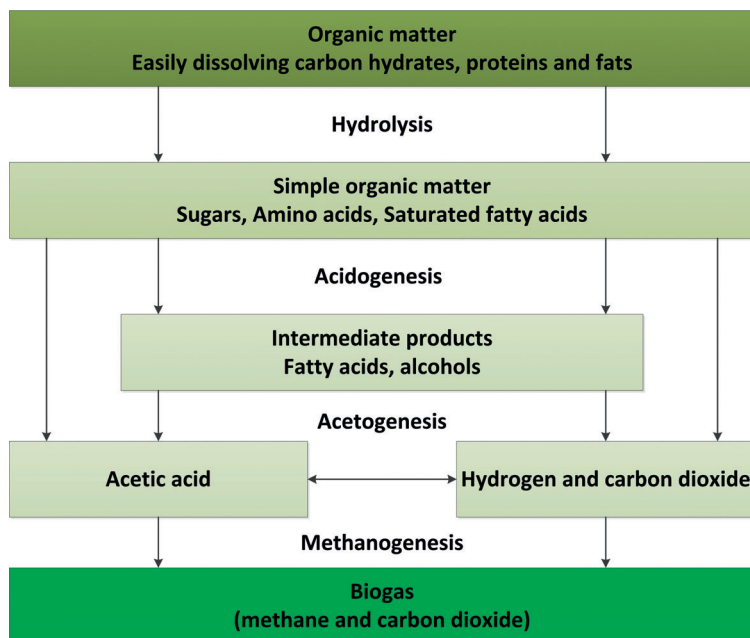


Figure 6.1 Phases of anaerobic digestion Adapted from (Biokaasun tuotanto maatilalla. page 4)

## 6.1 ANAEROBIC DIGESTERS

Anaerobic digesters allow biogas production under a controlled environment, thus allowing more optimized gas production compared to the naturally occurring anaerobic reactions (landfills and swamps). Utilization of anaerobic reactors has a long tradition in China and India.

The following Figure 6.2 illustrates the anaerobic reactor process in practical applications. The first stage is the feedstock input into the anaerobic reactor or to the hygienization chamber if needed. The biogas produced can be used directly in the CHP-process or upgraded to the natural gas grade bio-methane. The digested sludge formed in a biogas reactor can be used as agricultural fertilizer, which returns the micro- and macronutrients into circulation. Biogas production can be considered to be CO<sub>2</sub>-free since organic matter used as feedstock absorbs CO<sub>2</sub> from the air during growth. Even though the CO<sub>2</sub> is released from biogas production, refining and utilization, CO<sub>2</sub> stays in short circulation thus meaning that the process can be considered as CO<sub>2</sub>-neutral.

Typical components of biogas			
Methane	CH <sub>4</sub>	40 - 75	[%]
Carbon dioxide	CO <sub>2</sub>	25 - 45	[%]
Nitrogen	N <sub>2</sub>	1 - 15	[%]
Water vapor	H <sub>2</sub> O	4 - 7	[%]
Oxygen	O <sub>2</sub>	0 - 5	[%]
Hydrogen	H <sub>2</sub>	0 - 3	[%]
Hydrogen sulfide	H <sub>2</sub> S	0.1 - 0.5	[%]
Carbon monoxide	CO	0 - 0.3	[%]

Table 6.2 Typical biogas components and their concentrations

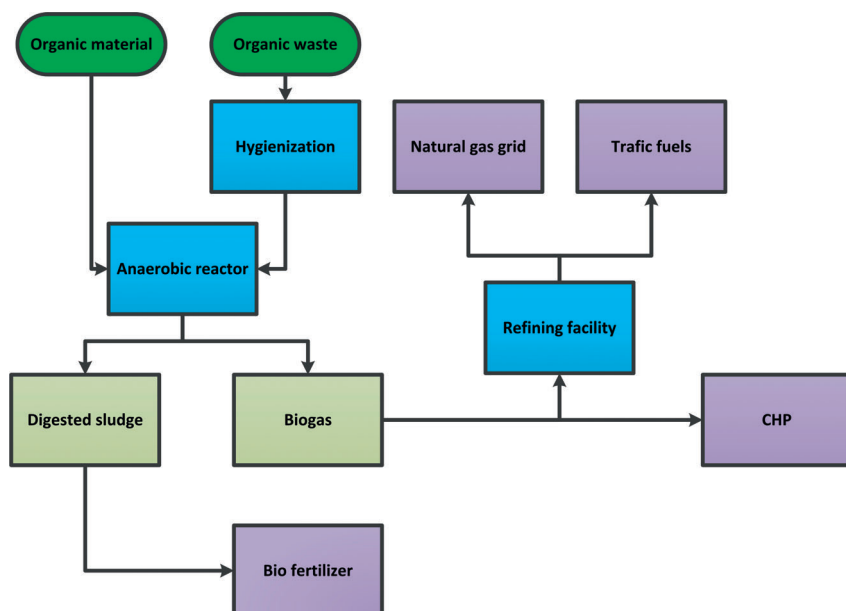


Figure 6.2 Anaerobic digestion from feedstock to products

Anaerobic digesters can be characterized into different groups by the temperature used and solid content of the sludge. Thermophilic, mesophilic and psychrophilic reactors are defined by the temperature used. The solid content of the sludge defines whether the reactor is a wet anaerobic reactor or dry anaerobic reactor. The wet reactors are considered to be reactors with a dry matter content of less than 15% and dry reactors are considered to be reactors exceeding 15% of dry matter content. Reactors can also be divided by the number of the stages of the reactors or whether the reactor is continuously working or batch loaded. Single-stage and two-stage reactors are commonly used but there also are processes utilizing three-stage reactors. Two-stage reactors are often utilized due to their possibility of high optimization of both reactor stages. The reactors can also be divided into large-scale and small-scale reactors (Woodhead Publishing Limited, 2011. page 277-279).

In biogas production, continuous working reactors are mostly used on a commercial scale. Continuous flow reactors require steady input and output flow. These types of reactors are often industrial-size and contain sophisticated automation systems. Reactor construction has many variations such as single and multiple tanks from horizontal to vertical builds. Compared to the batch reactors, which require loading and unloading between batchers, the continuous reactors provide uninterrupted biogas production (Biogas Handbook. 2008. Page 76).

The following figure illustrates a Chinese-type anaerobic digester. The typical size of the reactor is less than 10 m<sup>2</sup>. It is one of the commonly used reactors and does not require stirring or an automatic control system to work. Feedstock is added daily in batches and a similar amount is removed at the same time, thus it is a semi-continuous reactor type (Biogas handbook 2008. Page 31).

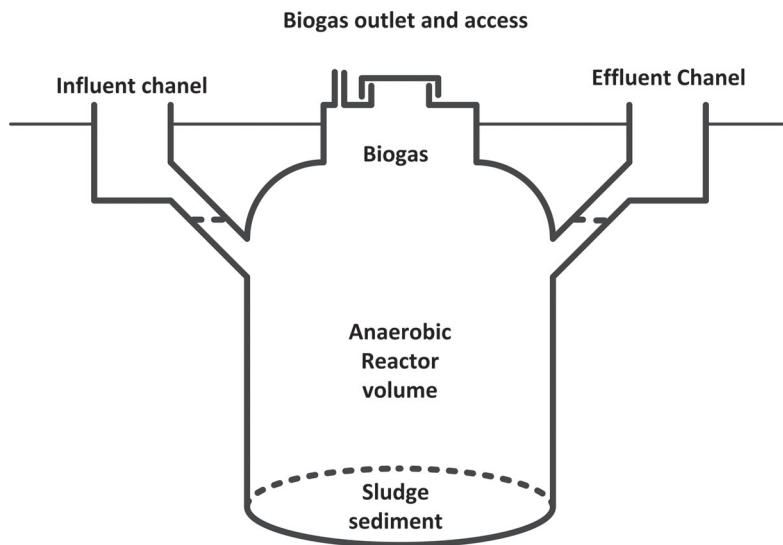


Figure 6.3 Chinese biogas reactor (Biogas Handbook. 2008. Page 31)

As previously mentioned, there are multi-phase biogas digesters that allow more optimized biogas production. Schematic Figure 6.4 presents a two-stage anaerobic digester. This type of reactor has potential for greater biogas production due to the possibility of more precise optimization.

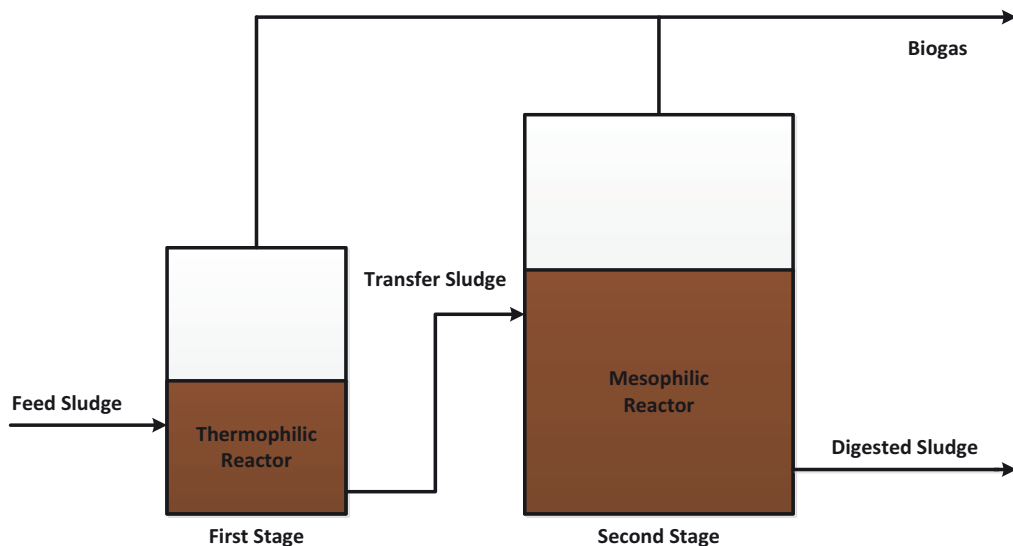


Figure 6.4. Two-staged anaerobic digester (Biogas Plant Constructions. page 9)

6.2 LANDFILL GAS

Organic substances brought to landfill start to decompose in aerobic and anaerobic conditions. Biogas is formed through anaerobic reactions. The composition of the biogas varies significantly compared to the controlled anaerobic digesters, because of the landfill’s variable feedstock. The composition of gas is also affected by various other factors like the moisture of the waste and the shape and size of the landfill (Clarke Energy. Landfill Gas).

Biogas production does not start immediately after a new landfill is established since anaerobic decomposition require the absence of oxygen. On the surface, organic waste decomposes through aerobic digestion. Usually, after two to three years from setting up the landfill, the biogas production through anaerobic digestion starts. Anaerobic biogas production usually lasts from 15 to 25 years. During this time, the biogas production of waste is slowly diminished, but this can be compensated by filling the landfill with additional organic waste (Clarke Energy. Landfill Gas).

Landfill gas usually has a calorimetric heat value of 3.5 to 5.5 kWh/m³(n). This roughly equals a methane content of 35% to 55%. In some cases methane content could be as high 65%. Produced biogas may include significant amounts of nitrogen, oxygen and other compounds due to the variable feedstock composition.

Usually landfill gas is collected by building a pipe network inside the landfill. There are horizontal and vertical piping solutions and also combinations of both. Landfill gas is drained from the pipe network using compressors. Before feeding the landfill gas into gas turbines or combustion engines, the landfill gas should be purified to prevent sulfur and silicon deposits.

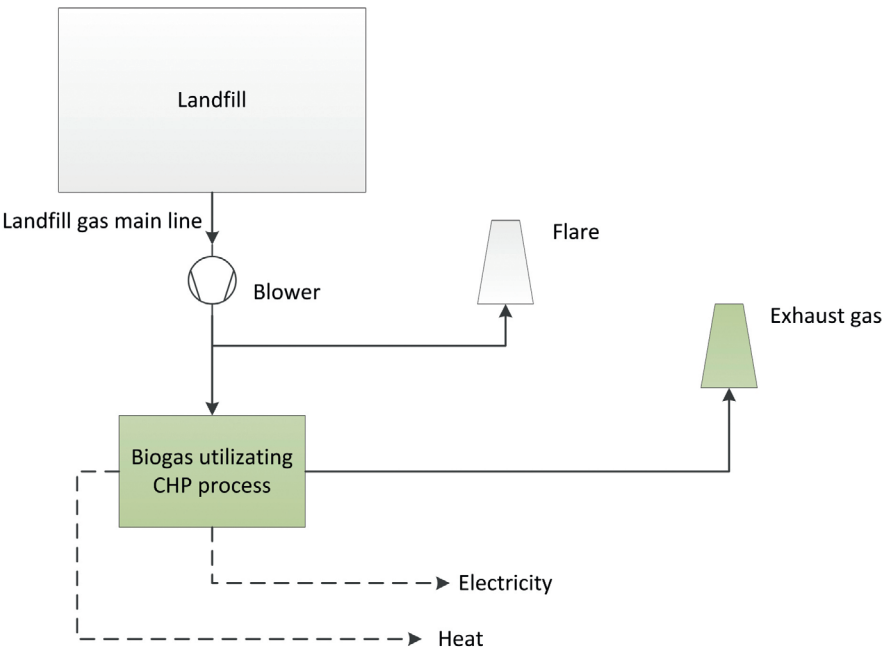


Figure 6.5 Example of landfill gas utilization. Adapted from (Clarke Energy. Landfill Gas).

The main obstacle to landfill gas utilization in electricity production is the higher portion of impurities than in biogas produced in a controlled process. Siloxanes and hydrogen sulfide easily choke activated carbon filters in a short period. Landfills with landfill gas recovery systems usually have flares in order to burn gases with excessively high hydrogen sulphide concentration.

Methane poses risks at landfills because it is flammable. Methane, in most cases, escapes in large quantities from landfill even when landfill gas recovery is implemented. This leads to elevated risk of fire and the potential danger of explosion at landfills. However, methane has quite a narrow explosion range (5 – 15 V%) so it is unlikely to explode. There are also other flammable or explosive gases present at landfills, which could contribute to the risk of fire or explosion.

Issues to be taken into account when dealing with landfill gas utilization:

- Leachate from landfill
  - Formation of toxic compounds
  - Formation of low pH solutions
- Explosion risk
  - Concentration of methane
  - Mixture of a different gases
- Risk of fire
  - Combustive material
  - Flammable gases
- Odours
  - Sulfide compounds
  - Particulates
- Greenhouse gases
  - Methane
  - CO<sub>2</sub>

### 6.3 BIOGAS TREATMENT AND UPGRADING

Biogas upgrading is required when biogas is to be used as a transport fuel or fed into the natural gas grid. The upgrading process increases the methane content of biogas. There are several upgrading methods such as. **high-pressure scrubbing**, **chemical scrubber**, **porous layer filtration**, **membrane separation** and **cryogenic purification**. **Water and moisture removal** may also be necessary before or after the aforementioned upgrading methods.

**A high-pressure scrubber** utilizes water for CO<sub>2</sub> and H<sub>2</sub>S removal. This method is considered to be the most cost-effective way to remove carbon dioxide and hydrogen sulfide from the biogas without absorbing a significant portion of CH<sub>4</sub>. This method is based on the difference of the gas component absorption coefficient (Dirkse Milieutechniek. Upgrading biogas).

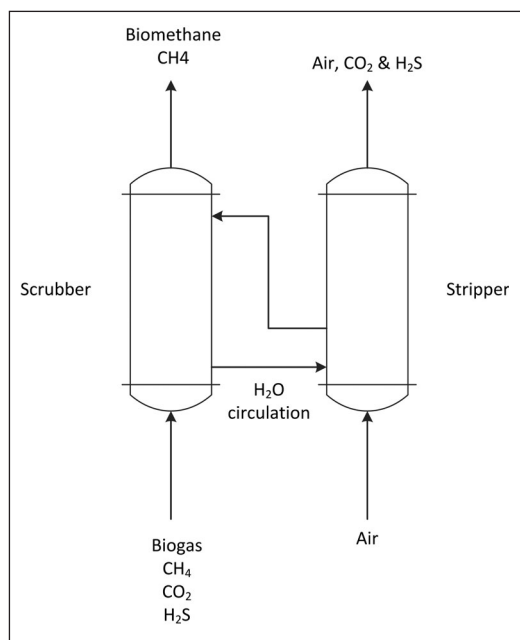


Figure 6.6 Basic principle of a high-pressure scrubber

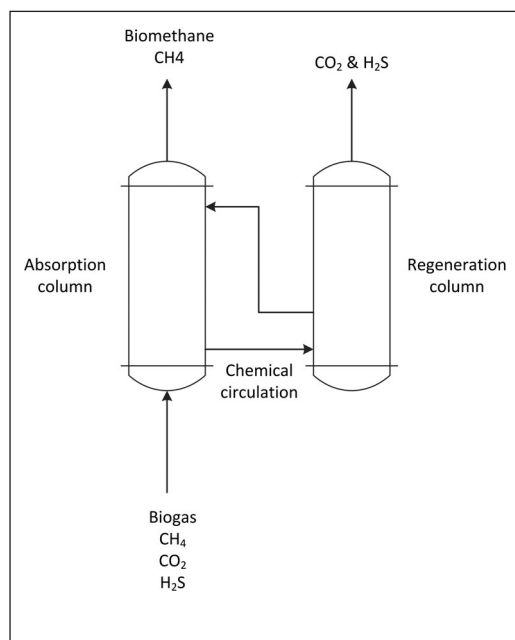


Figure 6.7 Basic principle of a chemical scrubber

**A chemical scrubber** utilizes water and chemicals, but this method does not require high pressure. The process utilizes chemical solutions to remove unwanted gas components: iron chelate for  $\text{H}_2\text{S}$  removal and amino acid salt solution for  $\text{CO}_2$  removal (Dirkse Milieutechniek. Upgrading biogas).

**Porous layer filtration** utilizes material with high porosity (activated carbon, zeolite and zinc dioxide), which adsorbs some gas components from biogas.  $\text{CO}_2$  and  $\text{H}_2\text{S}$  are adsorbed in higher portions than  $\text{CH}_4$  which makes filtration a viable solution. Filtration is based on adsorption on the surface of highly porous materials. There are two main methods utilizing adsorption in biogas upgrading: pressure-swing adsorption (PSA) and temperature-swing adsorption (TSA). PSA is based on changes in pressure while TSA is based on variations in heat (Dirkse Milieutechniek. Upgrading biogas).

**Membrane separation** is based on a semi-permeable surface. This surface is selective based on molecules. There are various membrane types, which can be utilized in biogas upgrading such as liquid membranes, metal membranes, ceramic membranes and polymeric membranes (Dirkse Milieutechniek. Upgrading biogas).

**Cryogenic purification** is an effective but expensive method for biogas upgrading. The requirement of high pressure and low temperatures will result in high building and operating costs. The method is based on liquefaction of gases in a distillation column (Dirkse Milieutechniek. Upgrading biogas).

**Water and moisture removal** is required since biogas contains water droplets and water vapor. The water removal can be one- or two-staged depending on the application. Usually pre-drying is done by slowing the gas flow in order to gravitationally separate liquid droplets from the biogas. Moisture removal is often done by cooling and compressing the biogas in order to condensate the water vapour (Landfill Gas Energy Utilization Technologies. Page 13)

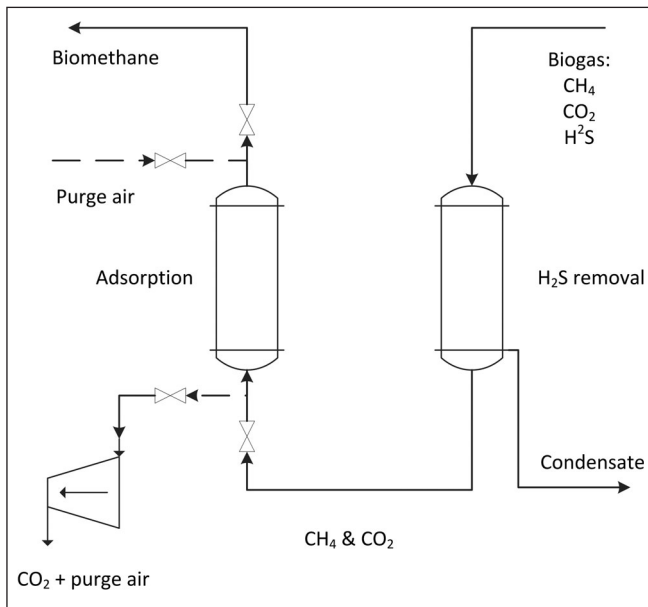


Figure 6.8 Basic principle of adsorption filter and hydrogen sulfide removal

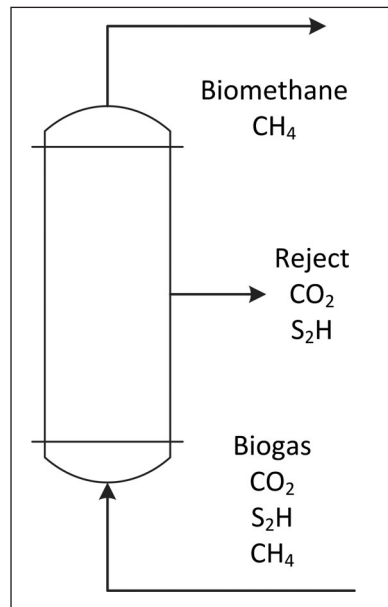


Figure 6.9 Basics of membrane filtering

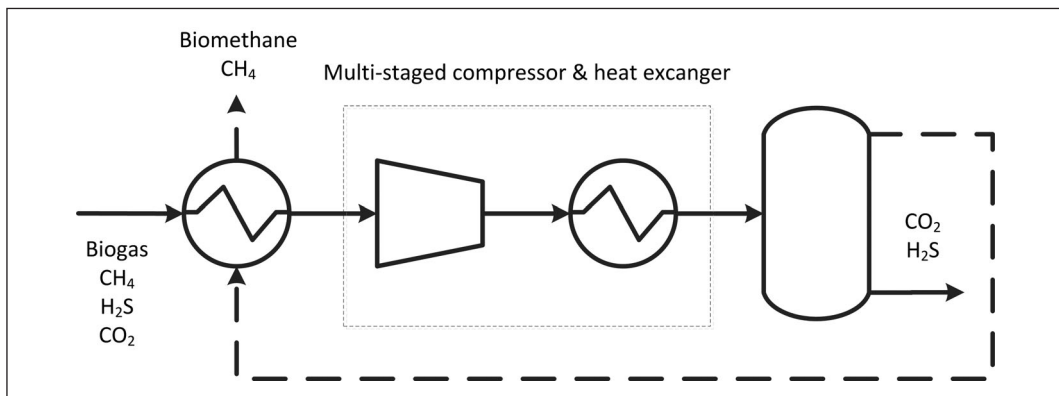


Figure 6.10 Basics of cryogenic filtering

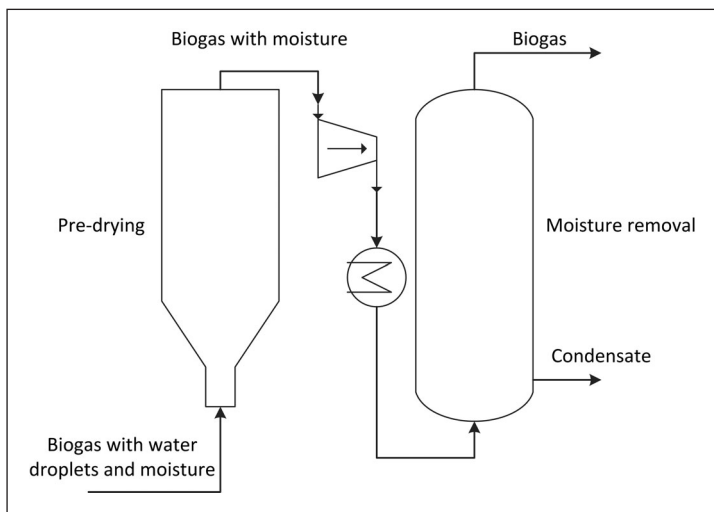


Figure 6.11 Basics of two-staged water removal



# 7 CASE STUDIES

## 7.1 KOTKAN ENERGIA HYÖTYVOIMALA

The waste-to-energy power plant in Korkeakoski is owned and operated by Kotka Energia. Construction of the waste-to-energy power plant started in August 2006 and the plant has been running on a commercial basis since April 2009. The plants fuel capacity is 34 MW and it is Finland’s first municipal waste-to-energy power plant. Investment costs for the power plant were €60 M (Kotka Energia).

The main fuel for the waste-to-energy power plant is pre-sorted household waste. Presorted household waste should be cleared from all recyclable waste fractions like bio-waste, glass, metal and hazardous waste. The waste is collected from the area of East Uusimaa, Kymenlaakso, Päijät-Häme and Mikkeli, and the population in the aforementioned areas is over 500,000. The annual waste usage is about 90,000 tonnes, which corresponds to about 260,000 MWh annually. Natural gas is used as a supplemental fuel in order to ensure proper operation in situations where there is not enough waste or its quality is lower than expected. Natural gas is also used in start-up situations (Kotka Energia).

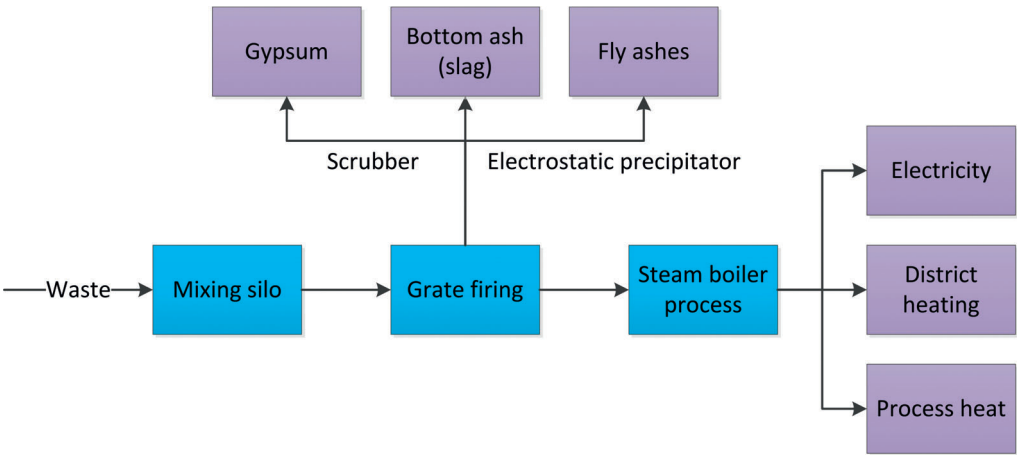


Figure 7.1 The basic waste-to-energy process

Kotka Energia’s waste-to-energy power plant utilizes the CHP-process in which heat and electricity are produced simultaneously. The heat is utilized in district heating and as process heat and the electricity is sold to the grid. The annual operating period is usually over 11 months and the plant should always operate at 100% capacity. The operating lifetime of the plant is estimated to be more than 20 years (Kotka Energia).

Figure 7.1 illustrates the basic design of the Korkeakoski waste-to-energy process. The waste is brought to the mixing silo by truck. A grab is used to mix and transfer the waste from the mixing silo to the grate where it is incinerated at a temperature over 1,000 °C. The steam boiler process is used to generate electricity, district heating and process heat from the hot flue gases. In normal operation, the plant produces 5 MW of electricity, 15 MW of process heat and 8 MW of district heating (Kotka Energia).

Korkeakoski waste-to-energy utilizes modern emission control systems, which ensure that the released flue gas meets strict emission limits. The plant utilizes a semi-dry flue gas cleaning system, which utilizes an electrostatic precipitator to remove the fly ash, a semi-dry scrubber to remove sulphur and acidic components and activated carbon to remove the dioxins and heavy metals. In addition, ammonia spraying is utilized to reduce NO<sub>x</sub> emissions. The semi-dry scrubber produces gypsum as a by-product, which can be used for example as a supplement. The fly ash from electrostatic precipitator can be utilized in landfill covering, among other things (Kotka Energia).

7.2 KYMEN BIOENERGIA, MÄKIKYLÄ BIOGAS PLANT

The biogas plant in Kouvola, Mäkilä, is owned by Kymen Bioenergia and operated by KSS Energia. Kymen Bioenergia is owned by three companies: KSS Energia, Kouvola Vesi and Kymenlaakson Jäte. Investment costs for the biogas plant were €7.2 M and, in an optimal situation, it produces about 13 – 14 GWh of biogas annually (Kymen Bioenergia) (Gasum).

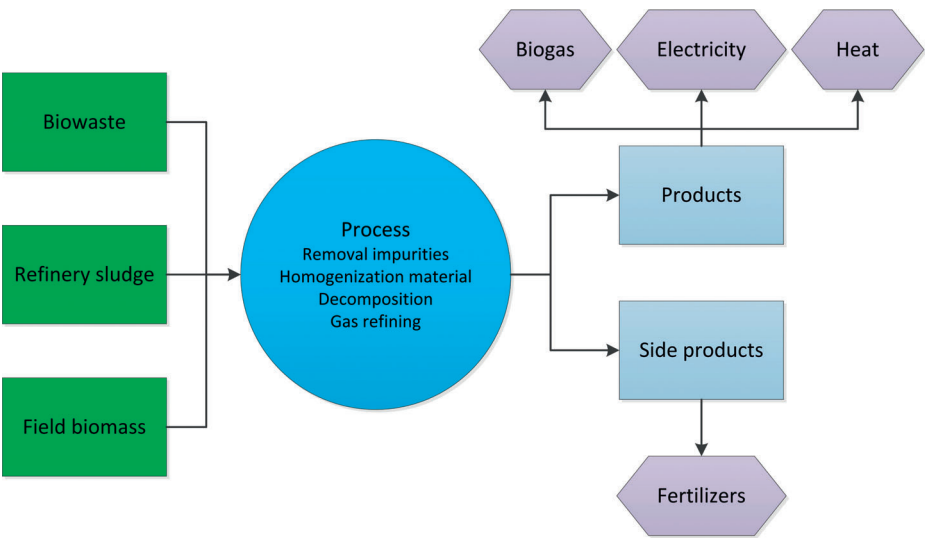


Figure 7.2 Basics of Kymen Bioenergia’s process

The Mäkikylä biogas plant was completed in spring 2011. The plant produces renewable energy in the form of electricity, heat and bio-methane. Bio-methane is fed into the natural gas system or used as traffic fuel. Annually the plant utilizes 19,000 tonnes of feedstock, which comprises sewage sludge around Kouvola, bio-waste around Kymenlaakso and local field biomass. By-products of the process include fertilizers produced from the digested sludge (Kymen Bioenergia. Yritysesittely).

Figure 7.2 shows the basic design of the production process. Bio waste (food sector, industry and households), refinery sludge (wastewater treatment plant) and field biomass (local fields) are fed into the process where they are removed of impurities, homogenized and decomposed into biogas. The biogas is then utilized in energy production or refined into bio-methane for the natural gas system. Hygienization of digested sludge is done by heating it to kill all harmful bacteria. Hygienized sludge is centrifugalized to increase the dry content of the sludge in order to use it as fertilizer (Kymen Bioenergia. Prosessi).

### 7.3 KYMENLAAKSON JÄTE, KELTAKANGAS WASTE MANAGEMENT CENTRE

Kymenlaakson Jäte Keltakangas waste management centre in Kouvola operates in field waste management and treatment, land filling and landfill gas utilization. The waste management centre was set up in 1997 by Kymenlaakson Jäte and is operated by Kymenlaakson Jäte. Waste is collected from following municipalities Virolahti, Miehikkälä, Hamina, Kotka, Pyhtää, Kouvola, Lapinjärvi, Iitti and Mäntyharju (Kymenlaakson Jäte).

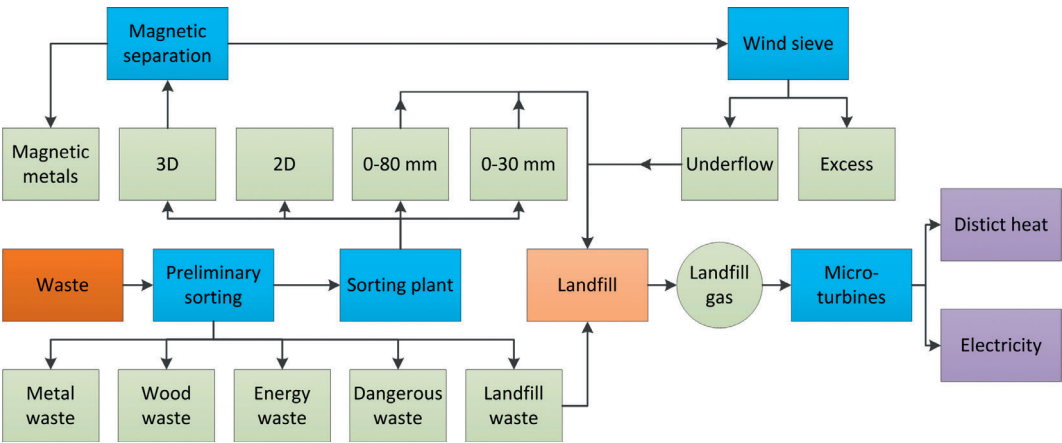


Figure 7.3 Basic design of waste processing. (Kymenlaakson Jäte)

Fraction	Usage
2D	Recycling fuel
0-80 mm	Waste-to energy plant or landfill
0-30 mm	Daily covering material for landfill
3D (air classifier excess)	For energy use after further treatment
3D (air classifier underflow)	Building material for support structure of landfill or road structures

Table 7.1 Sorting plant branch currents and their usage (Kymenlaakson Jäte)

Waste operations roughly consist of three parts; waste reception, waste treatment and waste disposal. Figure 7.3 illustrates the basic design of waste processing. First the waste goes through preliminary sorting, which sorts out most of the energy, metal, wood, hazardous and landfill waste from the waste stream for further processing. After preliminary sorting, the waste goes to the sorting plant. The sorting plant divides the waste into five fractions: 2D fraction, 0 - 80 mm fraction, 0 - 30 mm fraction, 3D (air classifier excess) and 3D (air classifier underflow). Table 7.1 illustrates the sorted fractions and their usage (Kymenlaakson Jäte).

Kymenlaakson Jäte has been collecting landfill gas from Keltakangas landfill since 2011. Landfill gas is collected utilizing a pipe network inside the landfill. Before feeding the landfill gas into a micro-turbine plant, it is cleaned of moisture and contaminants. The electricity (195 kW) from micro-turbines can be used for internal consumption or sold to the grid, and heat (335 kW) is used as process heat. Part of the landfill gas is burned in a flare as it contains too high a concentration of hydrogen sulfide (Kymenlaakson Jäte).

## 8 SUMMARY

This study was done for the project BLESK. This brief information package was based on the latest information on current legislation and the best available technologies. The need for more effective energy and biofuel production from organic waste streams comes from EU legislation. The EU has taken actions to prevent global warming, which some claim to be man-made. Diminishing sources of fossil fuels also create the need for renewable energy sources as a sustainable source of CO<sub>2</sub>-free energy.

As was pointed out in the chapter on waste streams, preventing waste forming is the most favored solution. However, this is hard to achieve and the amount of waste forming depends on many varying factors such as population and economy. This leads to the need for recycling and energy recovery to achieve more sustainable consumption.

Incineration of waste and co-firing waste with other fuels is considered to be a way to reduce the volume of landfilling and simultaneously produce energy. However, municipal waste has a low combustion heat, which is typically 3 to 5 MJ/kg. In the case of refuse-derived fuel, combustion heat is somewhat higher. Waste incineration is also subject to stricter regulations than conventional energy production. One could say that waste incineration is not the best solution for energy recovery from MSW.

Liquid biofuels have a great potential to replace fossil fuels if produced in a sustainable way. With developments in engine technology, biofuels can be used in almost any diesel and gasoline engines as a fuel supplement or alternative. Biodiesel, for example, can be seen as a potential additive for low sulfur petroleum diesel or even a substitute in some engines. Renewable diesel, however, is very similar to petroleum diesel and even superior in many properties, and as such can be used in any blend in almost any diesel engine. Bioethanol can be used as a fuel additive in current gasoline engines but, in order to harness the full potential of ethanol in internal combustion engines, engine development and modifications are needed in future.

Energy recovery done via anaerobic digestion or the production of biofuels is one way to utilize MSW. These technologies allow more effective utilization of organic waste streams. By-products such as digested sludge from anaerobic digestion can be used as fertilizer. This is one of the reasons why biogas production can be seen as a good way to process organic fractions of MSW. Biogas is also a flexible form of energy because of its wide range of utilization from CHP processes to

transport fuel.

Renewable energy is a developing area, which requires new innovations and a new kind of thinking to be a cost-effective way of producing energy. Political decisions play a major role in how the area will develop. However, sustainability and self-sufficiency create the need to replace fossil fuels. Waste is also something to ponder, because the ever-growing amount of MSW is something which must be dealt with. Effective utilization of waste has potential to provide materials, new products and energy while simultaneously reducing landfilling and GHG emissions.

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